

Aerobraking Trajectory Options for the First Mars Micro-Mission Telecom Orbiter

by

Dr. Daniel T. Lyons

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91109

daniel.t.lyons@jpl.nasa.gov

(818) 393-1004

ABSTRACT:

A small, interplanetary spacecraft is being developed for launch as a piggyback payload on the Ariane V. The spacecraft will be released during the intermediate Geosynchronous Transfer Orbit for the primary payload. The Micro-Mission spacecraft must carry sufficient propellant to leave Earth orbit and perform the remainder of the mission. Although missions to several target bodies have been discussed, the first mission will be to place a telecommunications satellite in orbit around Mars to act as a relay for other spacecraft at Mars. This first Mars Micro-Mission is scheduled to be launched in 2002 and arrive at Mars on December 26, 2003. Approximately 1400 m/s and several flybys of the Earth and Moon will be required to inject the spacecraft on a trajectory to Mars. Another 900 m/s will be required to capture the spacecraft into a highly elliptical orbit around Mars. Since nearly two thirds of the spacecraft mass must be propellant to provide enough ΔV just to reach Mars, aerobraking will be used to remove another 1190 m/s from a 72 hour capture orbit in order to shrink the apoapsis altitude to 800 km, for a nearly circular orbit required by the telecom system. This paper will discuss some of the tradeoffs associated with the aerobraking phase of the first Mars Micro-Mission.

THE MARS MICRO-MISSION SPACECRAFT

The 222 kg Mars Micro-Mission spacecraft has an unusual "banana" shape in order to fit into the allocated space for a "twin" configuration on the Ariane V Structure for Auxiliary Payloads (ASAP). Figure 1 shows a sketch of the JPL preliminary spacecraft design¹⁻³. (The final design will be determined by Ball Aerospace, the spacecraft contractor that was selected to build the spacecraft). In the preliminary design, four 22 N bi-propellant engines provide the thrust in the +X direction for the major maneuvers. Twelve smaller 1 N thrusters provide attitude control. Like the previous spacecraft which have used aerobraking, this spacecraft will probably have three (0.2 N-m-s) reaction

wheels for performing turns and for pointing the 0.8 m High Gain Antenna toward the Earth. Each of the two large tanks, one for hydrazine and one for oxidizer, is mounted over one of the two ASAP attachment points in order to minimize the structural loads at launch. The curved outer panel provides the structural surface for the solar cells and the support for the High Gain Antenna (HGA). Both the deployed HGA and the average solar cell normal point in the +Z direction. In the preliminary JPL design, most of the electronics are mounted on the panels at each end of the banana shape, as shown in Figure 1. (The mounting locations are arranged differently on the current design.) Flaps or inflatable fins must be deployed after launch to provide aerodynamic stability during the aerobraking phase of the mission, because calculations by the Aerothermodynamics Branch at the NASA Langley Research Center have shown that the preliminary spacecraft shape shown in Figure 1 is aerodynamically unstable. The aerobraking trajectories described later in this paper assume that the total projected frontal area is 4 m^2 with the stabilizing flaps extended, double the 2 m^2 maximum area without any flaps. The preliminary Ball design has a projected frontal area of only about 2.5 m^2 , which will require an aerobraking duration of about 4 months. The Micro-Mission spacecraft is approximately 2.49 m wide by 0.80 m high.

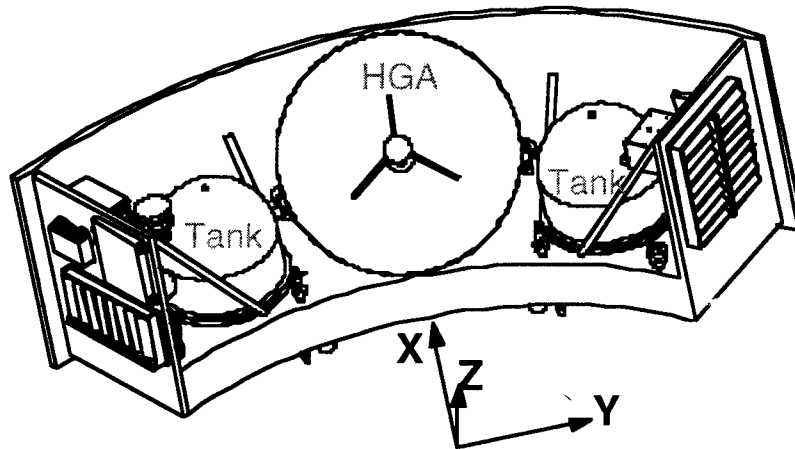


Figure 1: The Mars Micro-Mission Spacecraft Preliminary Layout.

MISSION DESCRIPTION:

Since the Mars Micro-Mission is being launched as a piggyback payload, the Micro-Mission must be able to adapt to the yet to be determined launch date of the primary payload. A strategy was developed by Paul Penzo⁴ where the spacecraft could wait in a loose orbit around the Earth for many months and use multiple Moon-Earth flybys to position the spacecraft for injection burn during one of the Earth flybys. The spacecraft cannot carry enough propellant to reach the desired final orbit, even if the entire 6 kg payload were converted into propellant. Instead, the spacecraft will be propulsively captured into a highly elliptical orbit with a period of 2 or 3 days. Several months of aerobraking are

needed to shrink the orbit period from a 72 hour period to a 2 hour period. Periapsis is propulsively raised out of the atmosphere to terminate aerobraking. The first orbiter will be placed into a nearly equatorial orbit, to maximize coverage of the planned landing sites. Later spacecraft will be placed into equatorial and inclined orbits to maximize the global coverage².

Once the relay orbit altitude is reached, omni antennas will provide the link to assets on the surface of Mars so that the body-fixed High Gain Antenna can remain pointed at the Earth and the body-fixed Solar Panel can collect power from the Sun. Data from the Mars assets will be recorded in the 800 Megabit solid state memory on-board the Micro Relay spacecraft, and then played back to Earth at 5 Kbps whenever a telecom link to Earth becomes available on the HGA (or 10 bps on the transmit only MGA). The spacecraft omni antennas provide an uplink capability of 7 bps from any attitude.

AEROBRAKING:

About 1400 m/s is required to put the spacecraft onto the interplanetary trajectory to Mars. Another 900 m/s is required to capture into a highly elliptical orbit around Mars. Another 1190 m/s is needed to reduce the apoapsis to 800 km. Since the 2300 m/s cumulative delta-V needed to reach the highly elliptical orbit will reduce the 222 kg mass at launch to 90 kg, there is not enough mass left to allocate enough propellant to supply the 1190 m/s required to reduce the apoapsis altitude from 78,000 km down to 800 km. Drag from the atmosphere will supply the ΔV required to shrink the orbit. About 160 m/s is required to raise periapsis propulsively to 800 km and circularize the orbit into the final 800 km relay orbit when aerobraking is finished.

Aerobraking is broken into three phases: Walk-in, Main, and Walk-out. The spacecraft will be captured into an orbit with a periapsis altitude at about 250 km, well above the atmosphere in order to accommodate navigational uncertainties associated with the approach trajectory. A series of several small propulsive maneuvers are used to gradually lower periapsis into the atmosphere to accommodate uncertainties in the atmospheric density. Although there is a very good chance that the atmospheric density will be within a factor of 2 of the models,⁵ sudden or unknown changes in the amount of dust in the atmosphere can change the density at aerobraking altitudes by an order of magnitude in the time required for a single orbit near the start of aerobraking.

The main phase begins when periapsis reaches an altitude where the drag is approximately equal to the planned, long term value required to shrink the orbit in the allocated time. Periodic propulsive "corridor control" maneuvers are required to maintain the drag in the appropriate range. Gravitational and solar perturbations tend to change the altitude of periapsis, while changes in the atmosphere tend to change the atmospheric density at a given altitude. If the density at periapsis becomes too large, then the spacecraft will be

overheated by the heat flux from the larger number of molecules that hit the spacecraft during the drag pass. If the density at periapsis becomes too small, then there won't be enough momentum transfer from the molecules hitting the spacecraft, and aerobraking will take too long. The magnitude of the propulsive maneuvers is small. A maneuver of only 0.1 m/s at apoapsis is needed to raise periapsis by 3 km near the start of aerobraking, when the spacecraft is in a highly elliptical orbit. As the orbit becomes more circular, the maneuver magnitude must increase by about a factor of about 6 to achieve the same change in the periapsis altitude.

The walk-out phase begins as the spacecraft approaches a circular orbit. Compared to the Mars Global Surveyor Mission, a walkout phase is not quite as important for this mission because the final apoapsis altitude is 800 km rather than 300 km, so the aerobraking exit maneuver (ABX) occurs further from the point where the spacecraft would spiral in and crash. It may also be possible to make the Mars Micro-Mission spacecraft operate more autonomously than the Mars Global Surveyor (MGS) spacecraft, where the 2 day orbit lifetime was dictated by the fact that every command had to be specified by ground control, and about 2 days were needed to regain control from a safe mode event. If the Mars MicroMission spacecraft is built with the capability to autonomously perform an Anti-Sun maneuver near apoapsis while in Safe-Mode, then the required orbit lifetime could be reduced to about 2 orbits (4 hours), short enough to eliminate the walkout phase. These trajectories assumed that a 1 day orbit lifetime would be required. Prudence requires at least one walkout maneuver to reduce the amount of apoapsis decay each orbit, so that the final apoapsis altitude could be targeted accurately.

TRAJECTORY OPTIONS:

Two aerobraking trajectory options will be discussed. The first trajectory was developed when a Mars airplane was still a possible option. In order to support the Mars airplane, this trajectory arrives on Dec. 12, 2003, several weeks earlier than the date that would minimize the ΔV required for capture. It was assumed that there would be sufficient propellant to capture into a 2 Sol orbit. The orbit period of the capture orbit would be adjusted after MOI such that the Micro-Mission orbiter would fly over the airplane and provide a data relay link during the short duration flight of the airplane. In this option, an aggressive aerobraking phase is used to show how rapidly the spacecraft might be able to reach the desired mapping orbit. The start of aerobraking in this example trajectory is delayed by 3 weeks after MOI to support any other assets that might be arriving at Mars and need support during this time frame. Many of the assets which the Mars Micro-Mission relay orbiter would like to support will arrive at about the same time as the Micro-Mission because that date requires the least energy to leave the Earth and arrive at Mars. Since aerobraking requires several months to gradually shrink the orbit from highly elliptical down to nearly circular, it may be necessary to provide support for these early missions from

the highly elliptical capture orbit, where the orbit period would be propulsively set to an integral number of Sols and the spacecraft location on the orbit phased to fly over a particular landing site. The duration of this potential elliptical operations phase will depend on the requirements of the assets that need support.

The second aerobraking trajectory option assumed that the ΔV margins were so bad that the spacecraft would be forced to capture into a 3 Sol orbit in order to reduce the capture ΔV by about 33 m/s. Furthermore, the MOI date was assumed to correspond to the minimum energy capture date, Dec. 26, 2003, which is unfortunately during the holiday season. Shifting the arrival date at capture 2 weeks later minimized the ΔV and decreased the MOI ΔV by 45 m/s compared to the other trajectory option. In this option, aerobraking was assumed to begin within a few orbits of MOI in order to reach the final relay orbit as soon as possible. A less aggressive aerobraking phase was used to illustrate that a more conservative aerobraking phase increases the duration of the two month aerobraking phase by a couple of weeks. The duration of the final design will depend on the thermal design of the spacecraft, as well as the size of the deployed aerodynamic stabilizers and the period of the initial capture orbit. (The current baseline has a projected frontal area of only 2.5 m² and requires 4 months for aerobraking.)

Table 1: Aerobraking Summary for 90 kg, 4 m² Spacecraft

| Tic on Plots | Blue "X" | Red "•" |
|------------------------------------|---------------------------|---------------------------|
| Period | 2 Sol (\approx 48 hrs) | 3 Sol (\approx 72 hrs) |
| Days of Aerobraking | 50 Days | 82 Days |
| Aerobraking Orbits | 115 Orbits | 190 Orbits |
| Average Dynamic Pressure | 0.68 N/m ² | 0.53 N/m ² |
| Average Qdot | 0.30 W/cm ² | 0.23 W/cm ² |
| Propulsive ΔV prior to ABX | 6.6 m/s | 7.8 m/s |
| MOI date | Dec. 12, 2003 | Dec. 26, 2003 |

Figure 2 shows the apoapsis altitude versus the number of days since Mars Orbit Insertion (MOI) for the two aerobraking options. Using the number of days since MOI for the horizontal axis makes it easier to compare the relative rates of decay for the more and less aggressive options, since the delay in the start of the shorter period, more aggressive option is about equal to the time required for the longer period, less aggressive option to reach the same apoapsis altitude. The start and end of the aerobraking phases for both options are marked by vertical dashed lines, which are labelled at the top. During the first two or three walkin orbits after the start of aerobraking, there is very little change in the apoapsis altitude because the dynamic pressures are very low. When the initial orbit period is three days, the first three walkin orbits require 9

days, about 11% of the total aerobraking duration. Comparing the 72 hour case to the 48 hour case shows that about 25 days were needed for the 72 hour case to “catch up” to the 48 hour case. Saving 33 m/s to capture into the larger 72 hour orbit adds 25 days to the aerobraking duration, other things being equal.

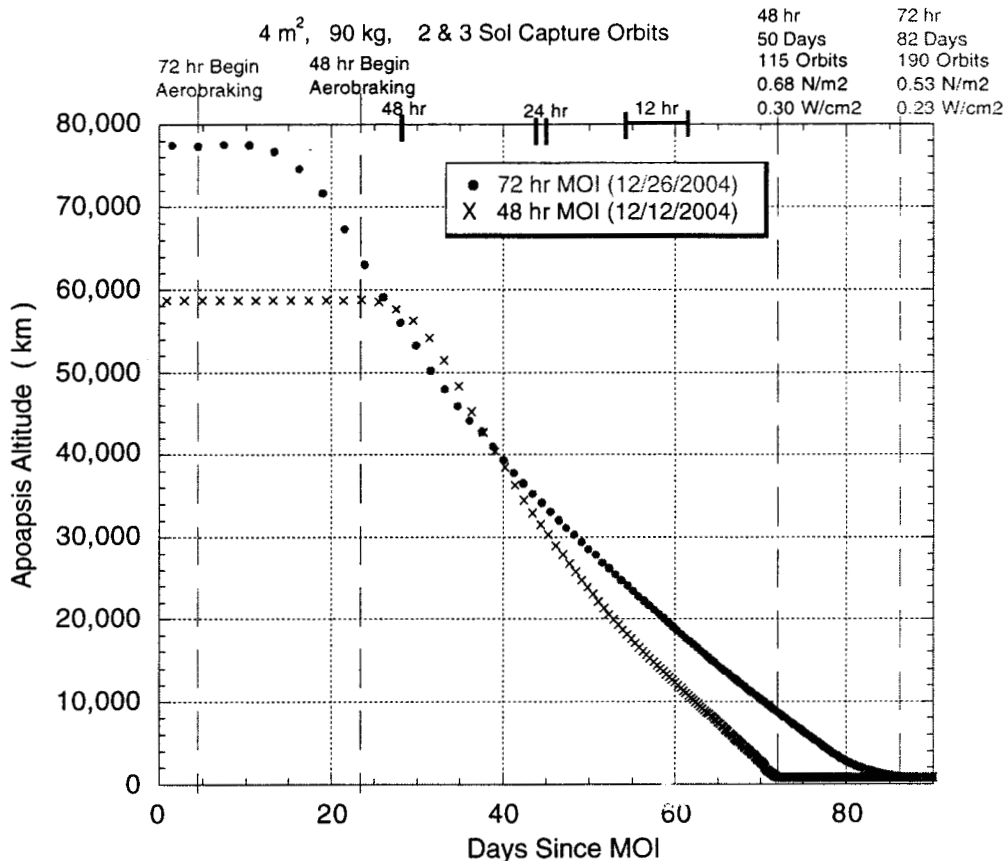


Figure 2: Apoapsis Altitude versus Days Since Mars Orbit Insertion

The difference in the slope of the apoapsis decay in Figure 2 is due to the difference in the dynamic pressure corridors, as illustrated in Figure 3. The original plan for the Mars Global Surveyor spacecraft still had about 100% heating margin at a dynamic pressure of about 0.6 N/m². (At least 100 % heating margin is required to accommodate atmospheric variability, which is more than 30% 1 sigma⁵⁻⁸. The maximum dynamic pressure actually experienced by the Mars Global Surveyor (MGS) spacecraft was 0.9 N/m² on orbit 15, where the maximum measured temperature was 92°C^{8,9}. During aerobraking, the most temperature sensitive pieces of hardware on the Mars Global Surveyor spacecraft were the solar panels. In order to achieve an aerodynamically stable configuration, the solar panels were swept back by 30° from head-on contact with the flow. The panel sweep also reduced the heat flux to the panels. Although the Micro-Mission configuration has not been finalized,

it is highly likely that some part of the solar panel will see the flow head-on, which means that direct comparisons between the Mars Global Surveyor and the Micro-Mission dynamic pressures and heat fluxes are not exactly correct. Furthermore, one of the MGS panels was broken, which allowed the panel to bend such that the effective sweep increased as the dynamic pressure increased^{9,10}, further reducing the heating effects. Since the required thermal margins will depend on the actual hardware design, the maximum dynamic pressure which corresponds to 100% thermal margin is not yet known. This comparison with the MGS value shows that these dynamic pressures are at least “in the ballpark” of the values which might be flown.

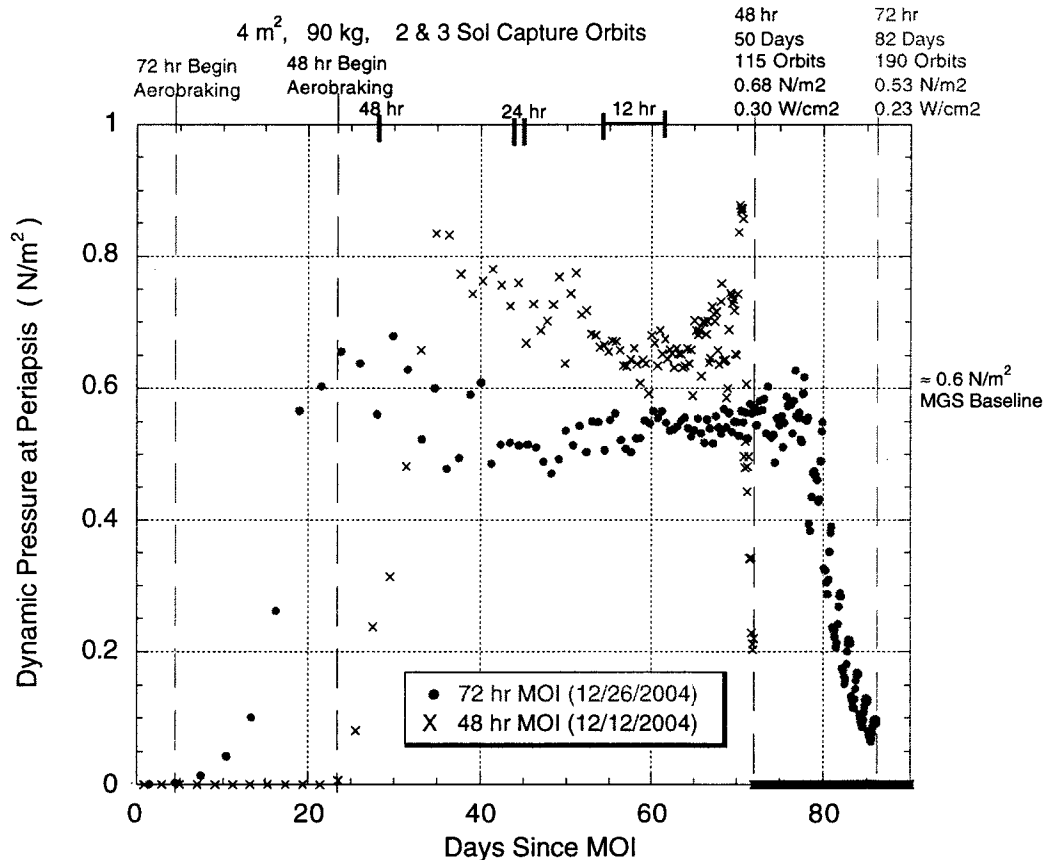


Figure 3: Dynamic Pressure at Periapsis versus Days Since MOI

The Velocity at Periapsis for the two cases is shown in Figure 4. The difference between a 48 hour and a 72 hour capture orbit is only 33 m/s. This figure shows that most of the velocity change occurs near the end of aerobraking, where the ΔV accumulates faster because there are more orbits per day. The reduced slope just before the Aerobraking Exit Maneuver (ABX) for the 72 hour case corresponds to the reduced dynamic pressures during the walkout phase, where periapsis is raised a little every day in order to guarantee a two day orbit lifetime.

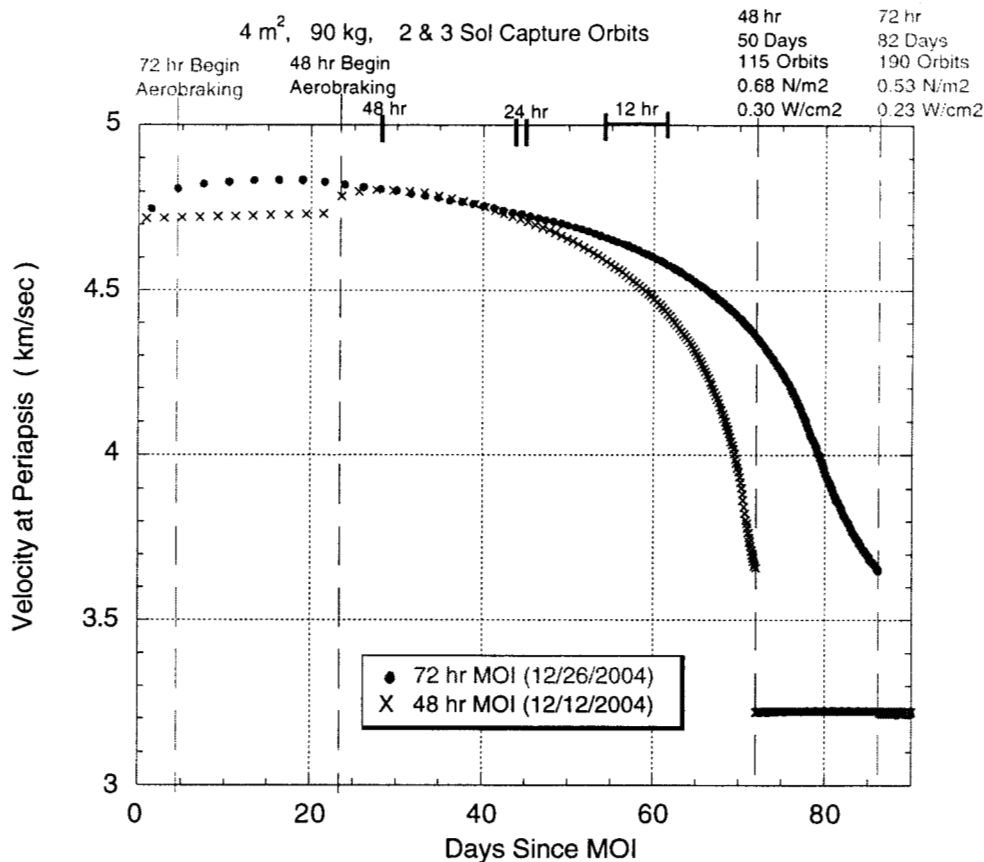


Figure 4: Velocity at Periapsis versus Days Since Mars Orbit Insertion

PROPULSIVE MANEUVERS:

Figure 5 shows the small propulsive ΔV maneuvers required to maintain periapsis in the desired corridor. Gravity perturbations from the non-uniform Mars gravity field and the Sun as a third body, and long term changes in the atmospheric density due to condensation and sublimation of the atmosphere at the poles are modelled⁵. Although less than 8 m/s is used in either case, the simulation does not include any short-term atmospheric variability, which can trigger more frequent corridor control maneuvers. About 15 m/s should be allocated for these corridor control maneuvers to accommodate the unmodelled atmospheric effects. Previous aerobraking missions have also included propellant for a "Popup" maneuver to temporarily raise periapsis out of the atmosphere in the event of an anomaly during aerobraking. The Mars Global Surveyor aerobraking phase⁵⁻¹⁷ at Mars required two popups, but the Magellan aerobraking phase^{8,19-30} at Venus did not require any popups. At Mars, a popup to an altitude of 150 km and the subsequent walkin costs 3 m/s when the orbit period is 72 hours, and 20 m/s when the orbit period approaches 2 hours.

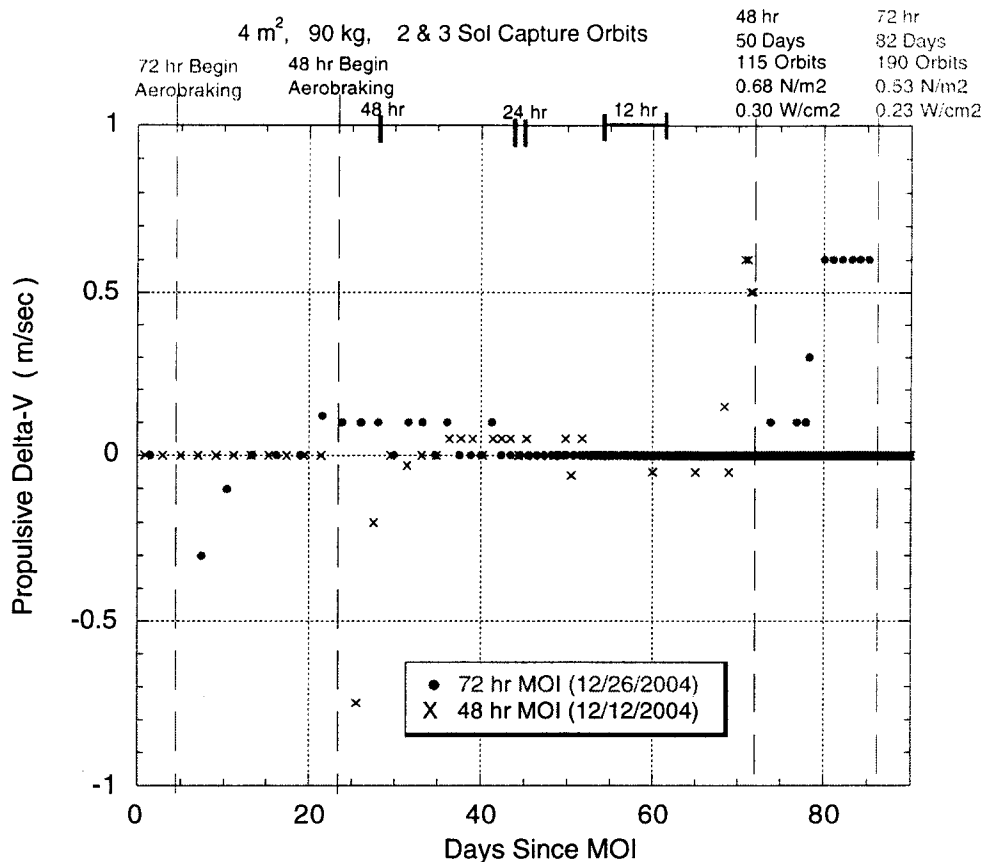


Figure 5: Propulsive ΔV versus Days Since Mars Orbit Insertion

POWER ISSUES:

Figure 6 shows that the drag duration remains close to 5 minutes for most of aerobraking, and then shoots up sharply to about 15 minutes as the orbit becomes nearly circular. During the drag pass, the spacecraft must be in the drag attitude that is determined by the vehicle aerodynamics. The spacecraft must turn to the drag attitude well before predicted atmospheric entry time, in order to accommodate uncertainties in the predicted entry time due to the effects of atmospheric density uncertainties on the orbit period. If atmospheric exit is not determined autonomously, an additional time must be allocated to the drag attitude to accommodate a lower than predicted drag on the preceding orbits. Finally, the duration of the turns to and from the drag pass attitude requires a finite amount of time, approximately 5 minutes for both Magellan and Mars Global Surveyor. Two 5 minute turns plus 5 minutes of timing margin at entry and exit plus the actual 15 minute drag duration add up to 35 minutes of time the spacecraft is not in an optimum solar power collection attitude. Thirty five minutes is 30% of the orbit period of the last aerobraking orbit.

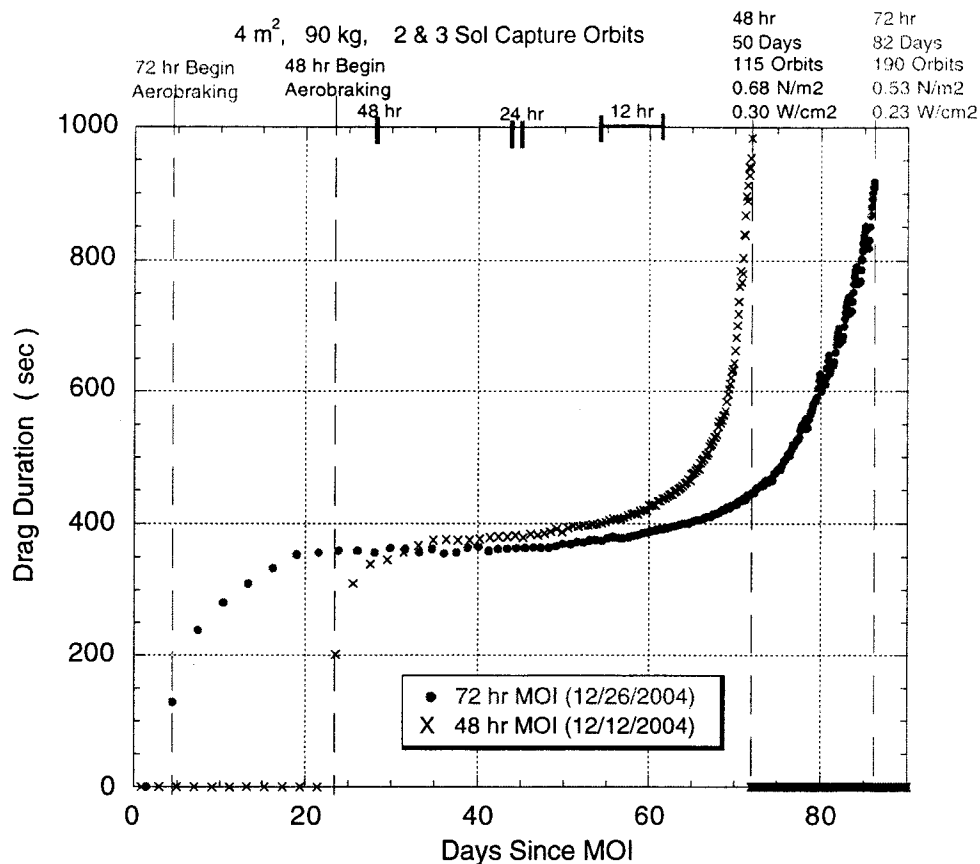


Figure 6: Drag Duration versus Days Since Mars Orbit Insertion

Eclipses have been an issue for polar orbit aerobraking missions, and are guaranteed to be a factor for low altitude equatorial orbits. Figure 7 shows the eclipse entry and exit times (individual points) relative the start and end of the turns to (green, nearly horizontal solid line) and from (green, nearly horizontal dashed line) the drag pass attitude, where "0" on the vertical axis represents the time since periapsis. A retrograde capture orbit was selected over a posigrade orbit because the posigrade orbit required aerobraking to be completed within about 6 months otherwise the eclipse duration could reach as many as 7 hours. The retrograde orbit did not experience any killer eclipses during the first two years that were simulated. As Mars moves around the Sun, there is a slow but steady change in the geometry of the Sun relative to periapsis. More importantly, the orbit precesses due to gravitational perturbations such that periapsis drifts out of the eclipse zone. As the orbit becomes more circular, the precession rate increases. Figure 7 shows that the overlap between the drag attitude and the eclipse zone becomes less as periapsis precesses out of the eclipse zone.

Since the drag attitude is usually not very good for generating power from the solar panels, the duration of the drag attitude becomes important near

the end of aerobraking when the orbit period is only about 2 hours. If the solar cells are in the shadow of the spacecraft for 35 minutes in the drag attitude and in the shadow of the planet for 50 minutes, and there is no overlap, then only 25 minutes are available for recharging the batteries. Although the battery capacity can easily accommodate a single 85 minute eclipse, there may not be enough time to recharge the batteries in only 25 minutes before the next 85 minute outage. The eclipse had to partially overlap the drag pass on the Mars Global Surveyor mission, where the final orbit apoapsis had to reach 400 km and the orbit period was 6 minutes lower. The seriousness of this issue will depend on the final design of the Micro-Mission spacecraft, such as whether power can be collected while in the drag attitude and the battery recharge rate.

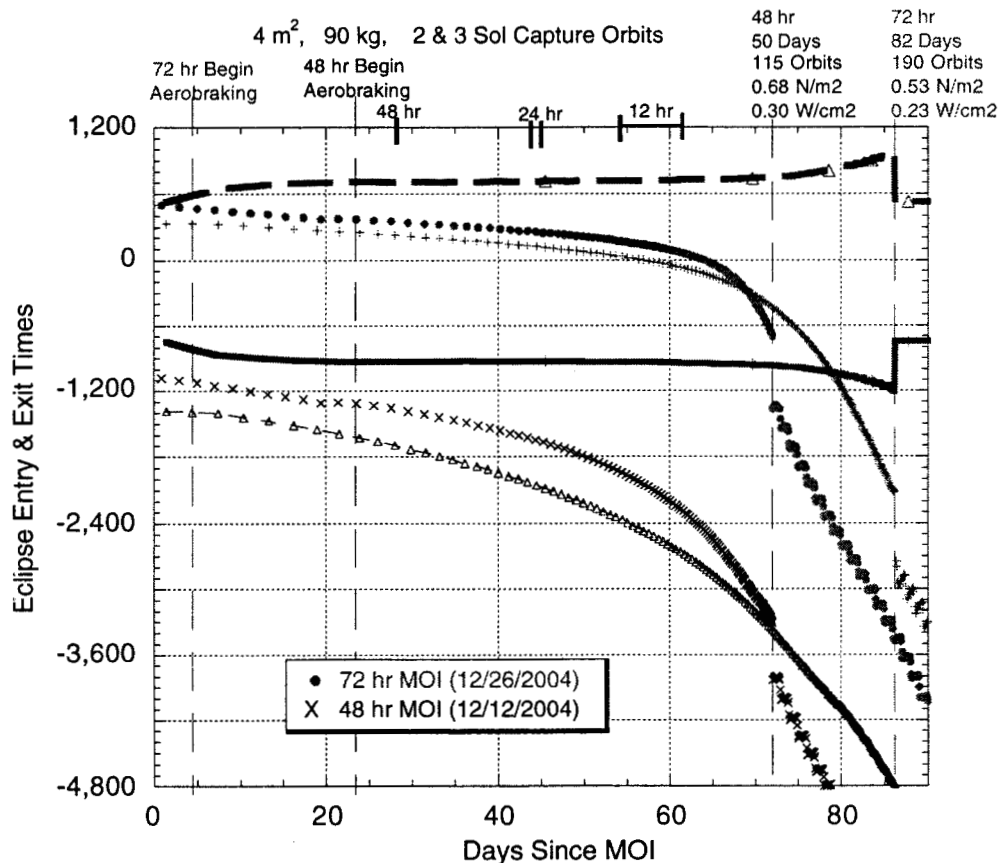


Figure 7: Eclipse Entry & Exit and Drag Attitude Start and End versus Days Since Mars Orbit Insertion

TELECOM:

Although previous failures, such as Mars Observer and Mars Polar Lander have demonstrated the need for real-time telemetry during critical events, obtaining telemetry is not always possible. Figure 8 shows the Earth Occultation entry and exit time for the two trajectories and the start and end of the turn to and from the drag attitude to illustrate that the critical data must be

recorded and played back later because the critical time near periapsis is always occulted. Even if Mars was not blocking the link to the Earth, the attitude of the spacecraft would allow at most a very low data rate signal through the omni antennas. Data from both the Magellan and Mars Global Surveyor missions had to be recorded during the drag pass and played back later in the orbit, so the lack of real time telemetry during the drag pass is not a new problem. Near the end of aerobraking, where at least part of the drag pass is visible from the Earth, power issues will probably preclude real time transmission from the drag attitude. Once the planned constellation is in place, it should be possible to obtain real time telemetry during most of the drag passes of future orbiters.

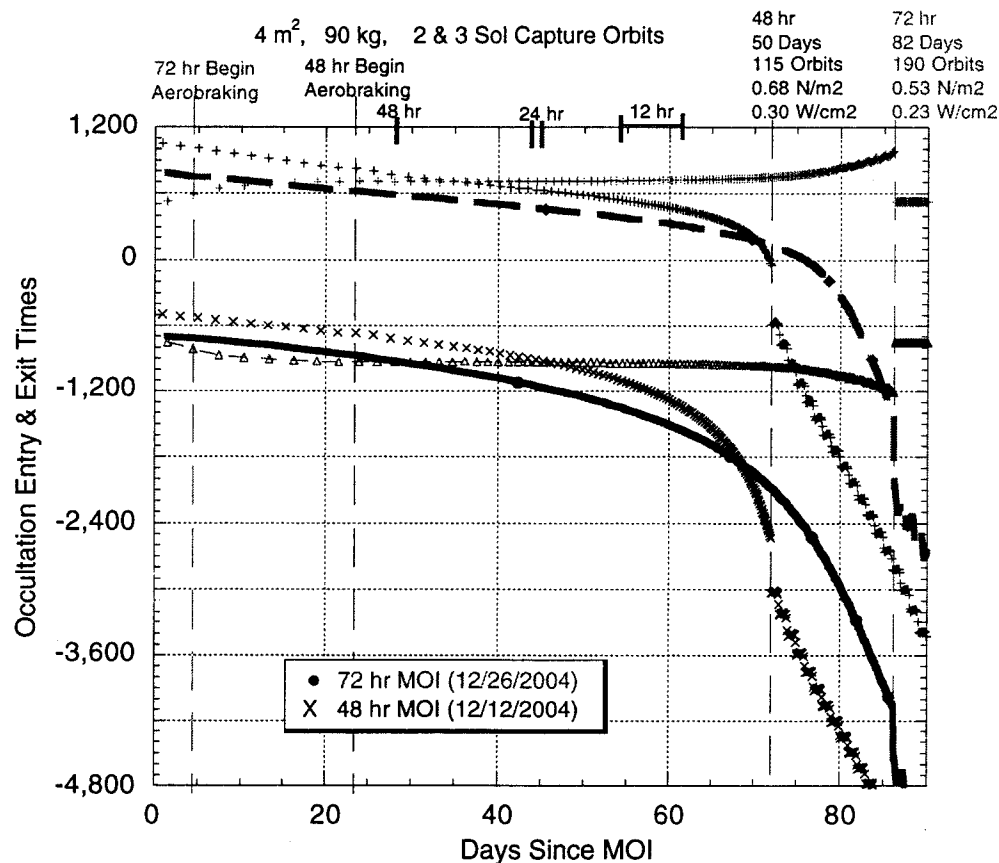


Figure 8: Earth Occultation Entry & Exit and Drag Attitude Start and End versus Days Since Mars Orbit Insertion

SEQUENCING ISSUES:

Figure 9 shows that the expected change in the orbit period can be more than 5 hours if the initial orbit period is 72 hours, or more than 3 hours if the initial orbit period is 48 hours. If an unusually large density is encountered during these early orbits, the period change could be double the expected

value in Figure 9. Since the 1 sigma variability in the atmospheric density from orbit to orbit is more than 30%, the uncertainty in predicting the time of the next orbit without knowledge of what happened during the previous drag pass can be an hour or more.

The Mars Global Surveyor mission started from a 45 hour capture orbit, and uplinked traditional sequences of commands for every event in the coming orbits even during the aerobraking phase^{8, 9, 12-15}. Nearly continuous tracking by the Deep Space Network was required in order to make this strategy work. The navigation team used tracking data from past orbits to infer what happened at each drag pass and then estimated the times of the coming orbits. Since the sequences only included a ± 5 minute margin for timing errors, the Navigation timing predictions were only good until the expected timing error was about 5 minutes. When the orbit period was large, it was impossible to predict through a single drag pass, because the 3 hour change in orbit period per orbit was so large that the atmospheric variability would have to be less than 3% to achieve a 5 minute timing prediction. The observed variability was more than 30%. During the early orbits, the navigation team had to obtain tracking data immediately after each drag pass in order to be able to predict the time of the next periapsis. Since the atmospheric uncertainty was no longer a factor, the time of the next periapsis could be predicted to within a few seconds. Unfortunately, a new sequence had to be built and uploaded before the next drag pass in order to incorporate this accurately predicted time.

Figure 9 shows that as the orbit shrinks, the change in the orbit period per orbit is reduced. By the time the orbit period reaches about 12 hours, where two MGS style sequences per day should be required, it becomes possible to predict through a single drag pass which has a 30% density offset from the predicted value with an accuracy of about 5 minutes at the next drag pass. Thus, when the orbit period was about 12 hours, only a single two-orbit MGS sequence had to be built and uplinked in a 24 hour period. The Mars Global Surveyor project found that this trend of smaller period change per orbit for larger numbers of orbits per day helped keep the number of sequences that had to be uploaded down to a manageable number. Even so, as many as three sequences were planned to be built and uplinked every day near the end of aerobraking. Since the broken solar panel forced MGS to fly at a dynamic pressure that was only half as large as originally planned¹⁰, only two sequences per day were actually required near the end.^{8,15,16} When the orbit period became very small, several orbits would pass before the new times could be predicted and the new sequence could be built and uplinked, so the start time of the first orbit in the new sequence would already be based on a prediction through several drag passes. If the Mars MicroMission sequences can be triggered by on-board measurements, then it would be possible to predict the start of the next drag pass much more accurately than the method used by the Mars Global Surveyor project.

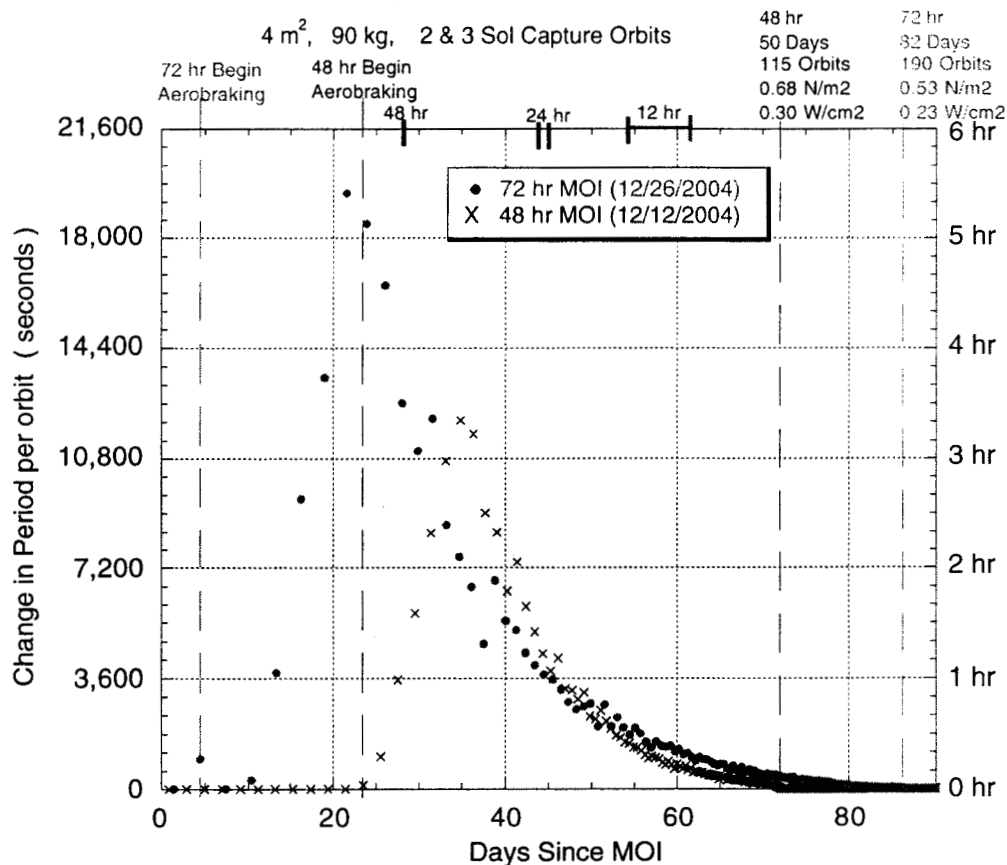


Figure 9: Change in Period per Orbit versus Days Since Mars Orbit Insertion

For Mars Global Surveyor, the 5 minute timing requirement was related to the fact that the attitude changes by about the width of the attitude thruster control deadband, 17° , in 5 minutes. Since the Mars Global Surveyor project chose to use a time-varying attitude reference, the maximum timing error that could be accommodated was about 5 minutes. The Mars Global Surveyor project used a time-varying attitude reference in order to minimize development costs by using existing flight software that was inherited from the Mars Orbiter project. Since the Mars Micro-Mission project is inheriting a different set of flight software, it may be possible to build a process that minimizes the amount of ground intervention that is required to operate the spacecraft during the aerobraking phase. Minimizing the data volume on the uplink could be especially important if the HGA is still stowed during the aerobraking phase. The time for every command had to be specified on the ground in advance for the Mars Global Surveyor spacecraft, even though the same set of commands were executed orbit after orbit for days at a time. Since the desired attitude at atmospheric entry is always well known, but the time of atmospheric entry is difficult to predict in advance, the magnitude of the attitude oscillations that occur during a drag pass could be greatly reduced by holding the desired inertial attitude for entry until drag is detected, and then autonomously switching

to the time varying reference. The time varying reference would have to be updated periodically to accommodate the orbit precession.

FURTHER SEQUENCE AUTOMATION OPTIONS:

In order to automate some of the repetitive task of determining the start time of the sequence of events for the next orbit on-board the spacecraft, the commands for one orbit of the Mars Micro-Mission spacecraft must be time-tagged relative to a single start time for that orbit. It will not be difficult for the spacecraft to determine when to trigger the start of the next orbit based on observations made during the preceeding orbit. The ground controllers would have the option to uplink a new sequence structure at anytime if events needed to be added to or removed from the sequence. Several spacing parameters, such as the duration of a drag pass, timing margins, and time from the start of the sequence to the time of the corridor control maneuver near apoapsis, could be stored in a table so that the sequence could be adjusted without uplinking a complete new sequence. By making some of the elements in this table functions of the orbit period, the amount of ground adjustment could be minimized. This approach would be similar to the Magellan sequencing strategy, where the sequence was an infinite loop. Rather than triggering the start of the sequence autonomously, the start of the next sequence was determined by reducing the orbit period by a constant value each orbit. This constant parameter had to be uplinked daily to keep the sequences in synch with reality.

Several approaches are available for triggering the start of the sequence for the next aerobraking orbit. Since the first Mars Micro-Mission spacecraft is in a nearly equatorial orbit, most orbits are eclipsed. Figure 7 shows that for these two retrograde trajectories, the eclipse entry always occurs before the start of the turn to the attitude required for the drag pass. Thus, one option for the first Mars Micro-Mission is to trigger the start of the sequence at entry into eclipse. Turning to the drag entry attitude at the start of the eclipse and holding that attitude until drag is detected would be one way to implement the sequence without any loss of solar power. Unfortunately, some of the mission options that have been studied have trajectories where some orbits are not eclipsed, so using eclipse entry is not a robust option. Furthermore, future missions at higher inclinations or a delay in aerobraking due to unforeseen circumstances, such as happened to MGS, may result in orbits with no eclipse or with eclipse entry during the drag pass.

Another option for triggering the start of the sequence for the next orbit is to use the accelerometer data to detect the time of the maximum deceleration during the previous drag pass, and then predict the time of the next maximum deceleration. The start of the turn to the drag attitude would be started a predetermined number of minutes prior to the expected entry into the atmosphere. The best design would combine the eclipse entry trigger with the

accelerometer prediction to make the system robust for the first mission, while building experience with the accelerometer approach for future missions. The accelerometer data could also be used to detect when the spacecraft exits the atmosphere, so that the spacecraft could turn back to the Sun point attitude as soon as possible and thus minimize the depth of discharge on the battery and maximize the recharge time - especially when the orbit period approaches two hours.

One difficulty associated with turning as soon as the drag disappears is that the propellant tank may require up to 10 minutes for the propellant to refill the propellant management device that prevents gas from entering the lines. The body rates induced during the drag pass would have to be kept low enough to be accommodated by the reaction wheels in order to perform the turn without damping out the body rate using the thrusters, as was done for both Magellan and Mars Global Surveyor.

DUST STORMS !

Figure 10 shows the Longitude of the Sun, L_s , versus the number of Days Since MOI for both trajectories. On a given date, the L_s is the same for both trajectories because L_s is only dependent on the location of Mars relative to the Sun. The reason for the offset is that the trajectory with the 48 hour capture period arrived at Mars two weeks earlier than the trajectory with the 72 hour capture. Scientists use L_s to measure the position of the Mars relative to the Sun. Large scale, planet encircling dust storms have only been observed when Mars is near perihelion. Although smaller dust storm activity can occur at any L_s , this period of higher dust storm activity has been labelled the dust storm season. Unlike the Mars Global Surveyor mission, which started aerobraking near the start of the dust storm season, the Mars MicroMission arrives near the end of the dust storm season. Thus, the first Mars MicroMission has a lower chance of encountering the start of a global dust storm during the aerobraking phase than MGS. Since the regional dust storm that occurred during the MGS aerobraking phase^{6,7,9} caused larger, more far reaching effects than predicted, a lower probability of a global dust storm is very good news. Unfortunately, the overlap between the aerobraking phase and the dust storm season occurs when the orbit period is very large so that there is time for the atmospheric density to change considerably from the last pass through the atmosphere. The danger can be mitigated by closely monitoring the atmosphere using other assets at Mars, like Mars Global Surveyor, or Earth based measurements such as those performed by Todd Clancy for the MGS operations project.

The start of a dust storm is extremely dangerous to an aerobraking mission because the dust can spread rapidly through the lower atmosphere, where it is heated by the Sun. The heat is transferred to the atmosphere, which expands as it is heated causing the entire column of atmosphere above it to rise up. This atmospheric expansion in the lower altitudes increases the densities at

the aerobraking altitudes even though no dust comes anywhere near the spacecraft, which never dips below 100 km. Detailed atmospheric simulations by scientists at NASA Ames Research Center and elsewhere have shown that a global dust storm can increase the atmospheric densities at the aerobraking altitudes by a factor of 10 in only a few days. Since the trajectory is designed with only a factor of 2 margin to accommodate the typical daily variability, a rapid density increase by a factor of 10 would destroy the spacecraft unless the periapsis is propulsively raised before the density increase becomes too large. Aerobraking at an altitude that would guarantee safety without requiring a periapsis raise maneuver in response to a dust storm would increase the duration of aerobraking to more than a year.

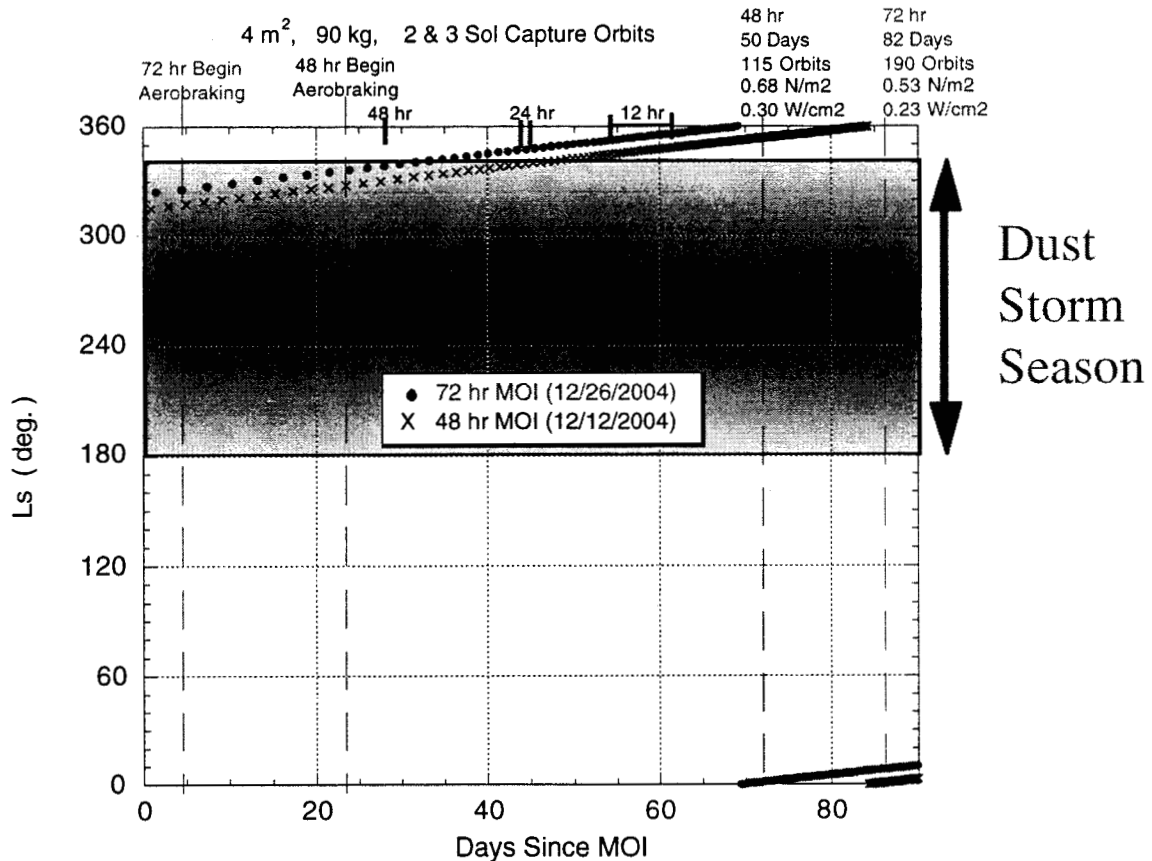


Figure 10: Longitude of the Sun, L_s , versus Days Since Mars Orbit Insertion

CONCLUSIONS:

A pair of preliminary trajectories which are representative of the aerobraking phase of the first Mars Micro-Mission have been discussed. Some of the impacts on the spacecraft design and operation were discussed. The overlap between the eclipse and the drag pass minimized power issues, except near the end of aerobraking where there may not be sufficient time to recharge the batteries unless the panels are sized large enough or the drag

attitude is such that solar power can be collected in the drag attitude. The eclipse entry may provide the easiest means for triggering the sequence of events that occurs every orbit, but it may not work for all mission scenarios. Accelerometer based sequence triggering is more robust, but requires more complicated on-board processing.

The duration of the aerobraking phase shown in these trajectories is based on a 4 m² projected frontal area baselined during the project proposal phase. The projected frontal area of the design selected from the proposal phase was only 2.5 m², which will result in a longer aerobraking duration than the trajectories shown here.

Ball Aerospace in Boulder, Colorado has been selected to build the first Micro-Mission spacecraft. The final aerobraking plan will be reported in the future after the spacecraft design is finalized.

ACKNOWLEDGEMENTS:

The work in this paper was performed at the Jet Propulsion Laboratory of the California Institute of Technology under contract with the National Aeronautics and Space Administration.

REFERENCES:

¹ California Institute of Technology, (RFP) NO. N18-4-8958, "Mars Micromission Spacecraft for Mars 2002 Missions(s)", June 22, 1999.

² R.J. Cesarone, R.C. Hastrup, D.J. Bell, D.T. Lyons, and K.G. Nelson, "Architectural Design for a Mars Communications & Navigation Orbital Infrastructure", AAS/AIAA Astronautics Conference, Girdwood, Alaska, August 1999. AAS 99-300

³ S. Matousek, K. Leschly, R. Gershman, J. Reimer, "Mars MicroMissions", 13th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 23-26, 1999, SSC99-VII-6.

⁴ P.A. Penzo, "Venus and Beyond Using the Ariane ASAP Launch Capability", AAS/AIAA Astronautics Conference, Girdwood, Alaska, August 1999. AAS 99-357

⁵ C.G. Justus, B.F. James, "Recent and Planned Improvements in the Mars Global Reference Atmosphere Model (MarsGRAM)", *Advances in Space Research*, 19(8), p 1223-1231, 1997.

⁶ Keating et.al., "The Structure of the Upper Atmosphere of Mars: First In Situ Measurements from an Orbiting Spacecraft", *Science*, Vol. 279, pp. 1672-1676, March 13, 1998.

⁷ Keating et.al., "Application of Accelerometer Data to Mars Global Surveyor Operations", *Journal of Spacecraft and Rockets*, Volume 36, Number 3, May-June 1999. pp. 323-329.

⁸ D.T. Lyons, "Aerobraking at Venus and Mars: A Comparison of the Magellan and Mars Global Surveyor Aerobraking Phases", AAS/AIAA Astronautics Conference, Girdwood, Alaska, August 1999. AAS 99-358

⁹ D.T. Lyons, J.G. Beerer, P.B. Esposito, M.D. Johnston, W.H. Willcockson, "Mars Global Surveyor: Aerobraking Mission Overview", *Journal of Spacecraft and Rockets*, Volume 36, Number 3, May-June 1999. pp. 307-313.

- ¹⁰ D.T. Lyons, "Mars Global Surveyor: Aerobraking with a Broken Wing", AIAA/AAS Astrodynamics Conference, Sun Valley Idaho, August 4-7, 1997. AAS-97-618.
- ¹¹ D.T. Lyons, "Aerobraking: The Key to Affordable Mars Exploration", 2nd International Low-Cost Spacecraft Conference, John Hopkins University, Applied Physics Laboratory, Laurel Maryland, USA, April 16-19, 1996, IAA-L-0512
- ¹² W. Lee, and W. Sidney, "Mission Plan for Mars Global Surveyor", AAS/AIAA Flight Mechanics Conference, Austin TX, Feb. 13-15, 1996, AAS 96-153
- ¹³ J. Beerer, R. Brooks, P. Esposito, D. Lyons, W. Sidney, H. Curtis & W. Willcockson, "Aerobraking at Mars: the MGS Mission", AIAA 34th Aerospace Sciences Meeting, Reno, 1/15-18/96, AIAA 96-0334.
- ¹⁴ S. Dallas, "The Mars Global Surveyor Mission", 1997 IEEE Aerospace Conference, Snowmass at Aspen, Colorado. Feb 1-8, 1997. pp. 173-179 of Proceedings.
- ¹⁵ M.D. Johnston, et.al. "Mars Global Surveyor: Aerobraking at Mars", AAS/AIAA Space Flight Mechanics Meeting, Monterey, CA, Feb. 9-11, 1998. AAS 98-112.
- ¹⁶ P. Esposito et. al., "Mars Global Surveyor Navigation and Aerobraking at Mars", 13th International Conference on Space Flight Dynamics, Goddard Space Flight Center, May 10, 1998. AAS 98-384.
- ¹⁷ R.G. Wilmoth, D.F. Rault, F.M. Cheatwood, W.C. Engelund, R.W. Shane, "Rarefied Aerothermodynamic Predictions for Mars Global Surveyor", *Journal of Spacecraft and Rockets*, Volume 36, Number 3, May-June 1999. pp. 314-322.
- ¹⁸ D.T. Lyons, W. Sjogren, W.T.K. Johnson, D. Schmitt, and A. McDonald, "Aerobraking Magellan", AAS/AIAA Astronautics Conference, August 19-22, 1991, Durango Colorado. Paper AAS-91-420.
- ¹⁹ D.T. Lyons, "Aerobraking Magellan: Plan versus Reality", AAS/AIAA Spaceflight Mechanics Meeting, Cocoa Beach Florida, February 14-16, 1994. Paper AAS 94-118.
- ²⁰ D.T. Lyons, R. Stephen Saunders, and Douglas Griffith, "The Magellan Venus Mapping Mission: Aerobraking Operations", 44th Congress of the International Astronautical Federation, Graz, Austria, October 16-22, 1993. Paper IAF-93-Q.4.409.
- ²¹ H. Curtis, "Magellan Aerobraking at Venus", *Aerospace America*, January 1994, pp 32-41.
- ²² R. Cook and D.T. Lyons, "Magellan Periapsis Corridor Design", AAS/AIAA Space Flight Mechanics Conference, Colorado Springs, Colorado. February 24-26, 1992. Paper AAS-92-159.
- ²³ W.H. Willcockson, "Magellan Aerobraking Control Corridor Design & Implementation", AAS/AIAA Spaceflight Mechanics Meeting, Cocoa Beach Florida, February 14-16, 1994. Paper AAS 94-117.
- ²⁴ A. Carpenter and E. Dukes, "Control of the Magellan Spacecraft During Atmospheric Drag", 17th annual AAS Guidance and Control Conference, Keystone Colorado, February 2-6, 1994. Paper AAS-94-064.
- ²⁵ H. Curtis, "Reconstructing Time of Periapsis from Spacecraft Telemetry during Magellan Aerobraking", 17th annual AAS Guidance and Control Conference, Keystone Colorado, February 2-6, 1994. Paper AAS-94-054.
- ²⁶ S.K. Wong, T-H. You, J.D. Giorgini, L. Lim, P. Chadbourne, "Navigating through the Venus Atmosphere", AAS/AIAA Spaceflight Mechanics Meeting, Cocoa Beach Florida, February 14-16, 1994. Paper AAS 94-116.
- ²⁷ J.D. Giorgini, S.K. Wong, T-H. You, L. Lim, P. Chadbourne, "Magellan Aerobrake Navigation", British Interplanetary Society, 1994.

²⁸ B.L. Haas and W.J. Feiereisen, "Particle Simulation of Rarefied Aeropass Maneuvers of the Magellan Spacecraft", Paper AIAA 92-2923. July 1992.

²⁹ B.L. Haas and D.A. Schmitt, "Simulated Rarefied Aerodynamics of the Magellan Spacecraft during Aerobraking". Paper AIAA 93-3676.

³⁰ D.F. Doody, "Aerobraking the Magellan Spacecraft in Venus Orbit", IAA International Conference on Low-Cost Planetary Missions, John Hopkins University, April 12-15, 1994. Paper IAA-L-0602.